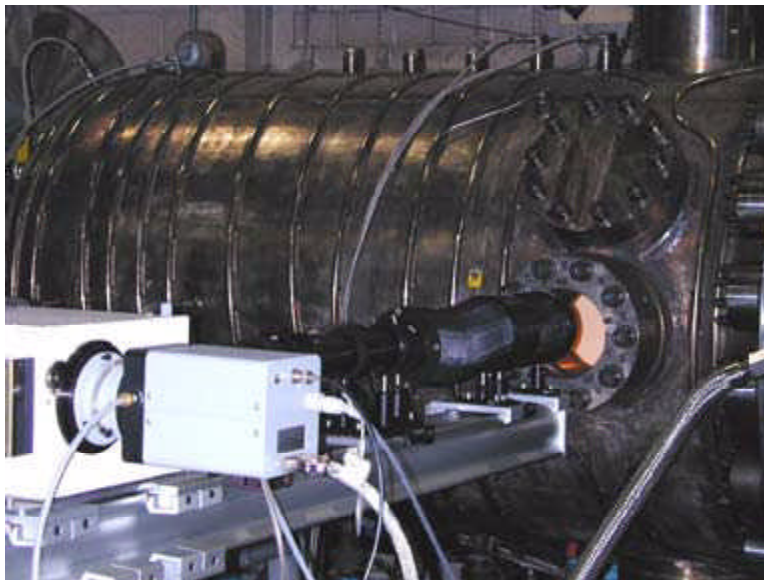


# One-Dimensional Spontaneous Raman Measurements of Temperature Made in a Gas Turbine Combustor

The NASA Glenn Research Center is working with the aeronautics industry to develop highly fuel-efficient and environmentally friendly gas turbine combustor technology. This effort includes testing new hardware designs at conditions that simulate the high-temperature, high-pressure environment expected in the next-generation of high-performance engines. Glenn has the only facilities in which such tests can be performed. One aspect of these tests is the use of nonintrusive optical and laser diagnostics to measure combustion species concentration, fuel/air ratio, fuel drop size, and velocity, and to visualize the fuel injector spray pattern and some combustion species distributions (refs. 1 to 2). These data not only help designers to determine the efficacy of specific designs, but provide a database for computer modelers and enhance our understanding of the many processes that take place within a combustor. Until recently, we lacked one critical capability, the ability to measure temperature. This article summarizes our latest developments in that area.

Recently, we demonstrated the first-ever use of spontaneous Raman scattering to measure combustion temperatures within the Advanced Subsonics Combustion Rig (ASCR) sector rig. We also established the highest rig pressure ever achieved for a continuous-flow combustor facility, 54.4 bar. The ASCR facility (ref. 2) can provide operating pressures from 1 to 60 bar (60 atm). This photograph shows the Raman system setup next to the ASCR rig. The test was performed using a NASA-concept fuel injector and Jet-A fuel over a range of air inlet temperatures, pressures, and fuel/air ratios.

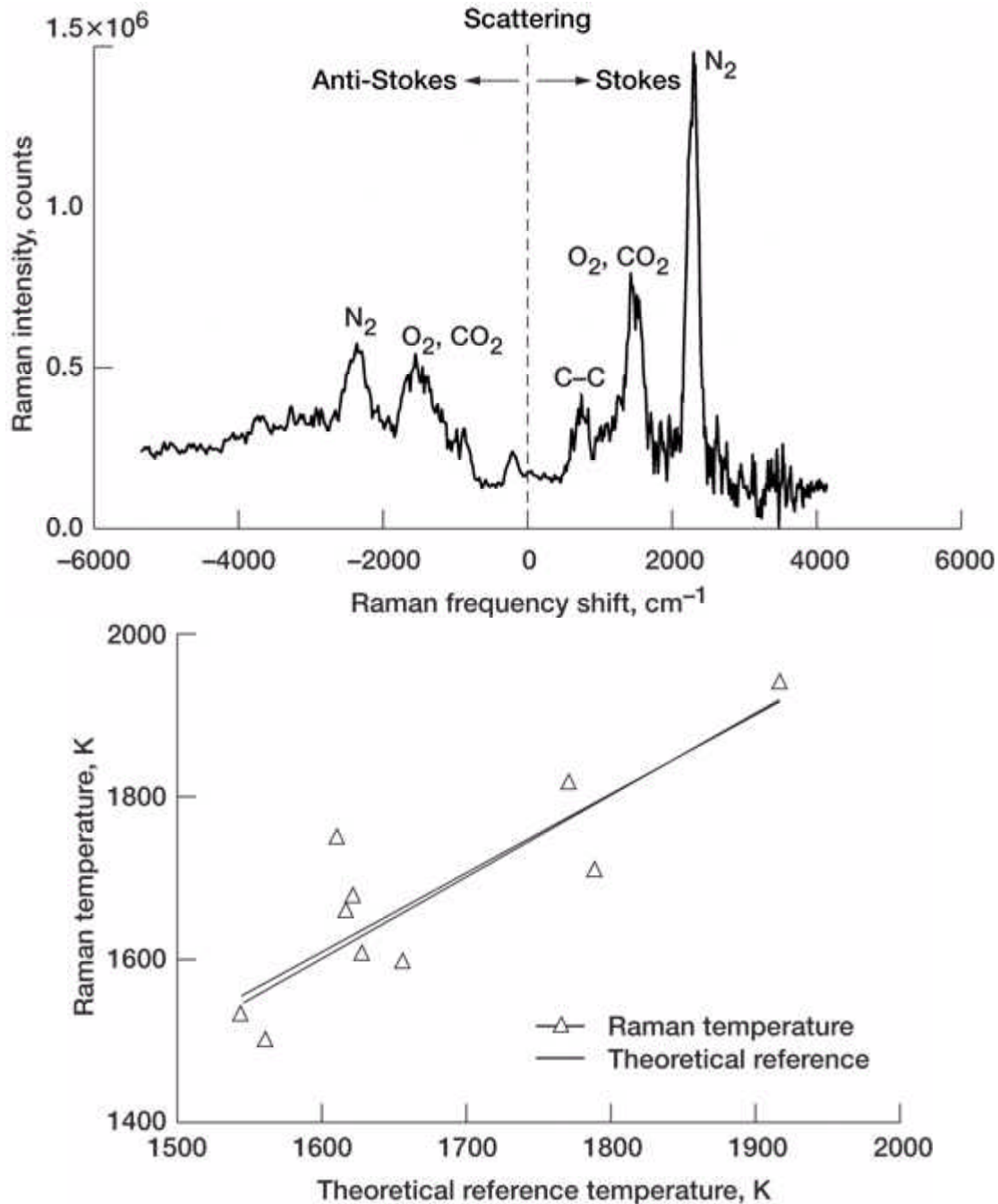


*Spontaneous Raman scattering experimental setup in the Advanced Subsonics Combustion Rig.*

Long description The laser beam enters the combustor vertically through the top window (just visible, top right). Scattering by combustion species is collected through the illuminated window by the Raman optics. The light is then spectrally dispersed by a spectrometer and imaged on a camera (foreground left).

Spontaneous Raman scattering allows one to measure combustion species (ref. 3) and/or temperature. The signal that one obtains is typically a spectrum whose peaks are linearly related to the number density of the molecular species. These peaks occur at characteristic intervals that depend on the physical characteristics of the molecular species, thus producing a fingerprint unique to that species and making this a good method for species measurement and identification. In Raman spectroscopy, that characteristic interval is the frequency shift from the laser light-scattering source. This frequency shift is related to the rotational and vibrational components of each molecule's energy at the time it encounters the laser, and it appears as a positive shift (Stokes scattering) when the molecule receives energy from the laser and a negative shift (anti-Stokes scattering) when the molecule gives up energy. The relative intensity of the Stokes and anti-Stokes peaks depends on the temperature that a system of molecules finds itself in, which follows a Boltzmann distribution. The ratio of the areas of the anti-Stokes peaks to the Stokes peaks for molecular nitrogen, an inert species whose molecular concentration remains relatively constant for any given test condition, is directly related to the temperature via Boltzmann statistics.

The left graph shows a typical Raman spectrum obtained during the test. The inlet temperature and pressure are 720 K and 54 bar. Molecular nitrogen and oxygen are present, as well as  $\text{CO}_2$  and fuel and its remnants as indicated by the carbon-carbon (C-C stretch). The temperatures measured using the Raman technique compare favorably with theoretical temperatures determined from the flow parameters, as shown in the bottom graph. Here, the Raman-derived temperatures are plotted with the theoretical temperatures derived from the flow conditions. Given these excellent results, we now have a very useful tool that will further enable us to develop next-generation combustor technology.



Left: Raman spectrum acquired during combustion. The abscissa is the Raman shift in wave numbers (reciprocal centimeters). The ordinate is the Raman-scattered intensity. The combustor pressure is 54 bar, the inlet temperature is 717K, and the fuel-to-air equivalence ratio,  $f$ , is 0.35. The theoretical temperature is 1560 K, and the Raman temperature is 1500 K. Right: Comparison of the bulk theoretical combustion temperature to the measured Raman temperature.

Long description: Left: The vertical dashed line indicates the laser frequency, zero shift. Shifts for which the molecules gain energy from the laser beam are called Stokes lines and appear to the right of the laser frequency. Conversely, the anti-Stokes lines result when higher energy molecules lose energy to the laser beam and appear to the left of the laser

frequency. The shift for each species depends on the rotational and vibrational energy. The O<sub>2</sub> and CO<sub>2</sub> peaks could not be resolved with this experimental setup. Right: The Raman temperature plot, shown as a linear fit to the red triangles, was calculated using the area ratio of the N<sub>2</sub> anti-Stokes /Stokes peaks for all test points. The green reference line is the theoretical temperature calculated from the inlet flow parameters measured during the test. There is little discrepancy between the two lines, demonstrating the viability of this Raman scattering technique for nonintrusive temperature measurement.

## References

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